

Effects of symmetry energy in the reaction $^{40}\text{Ca}+^{124}\text{Sn}$ at 140 MeV/nucleon

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The density dependent symmetry energy is a hot topic in nuclear physics. Many laboratories in the world are planning to do related experiments to probe the symmetry energy. Based on the semi-classical Boltzmann-Uehling-Uhlenbeck (BUU) transport model, we studied the effects of nuclear symmetry energy in the central reaction $^{40}\text{Ca}+^{124}\text{Sn}$ at 140 MeV/nucleon in the laboratory system. It is found that the rapidity distribution of free nucleon's neutron to proton ratio is sensitive to the symmetry energy, especially at large rapidities. The free n/p ratios at small or large rapidities may reflect high or low density behavior of nuclear symmetry energy. To probe the density dependence of nuclear symmetry energy, it is better to give the kinetic distribution and the rapidity distribution of emitted nucleons at the same time.

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I. INTRODUCTION

After about three decades of intensive efforts in both nuclear experiments and theories, the equation of state (EOS) of isospin symmetric nuclear matter is now relatively well determined mainly by studying collective flows in heavy-ion collisions and nuclear giant monopole resonances [1, 2]. The major remaining uncertainty about the EOS of symmetric nuclear matter is due to our poor knowledge about the density dependence of the nuclear symmetry energy [1, 3–7]. Therefore, the new challenge is to determine the EOS of isospin asymmetric nuclear matter, especially the density dependence of the nuclear symmetry energy. Besides the great interests in nuclear physics, the EOS of asymmetric nuclear matter is also crucial in many astrophysical processes, especially in connection with the structure of neutron stars and the dynamical evolution of proton-neutron stars [11]. Considerable progress has been made recently in determining the density dependence of the nuclear symmetry energy around the normal nuclear matter density. However, much more work is still needed to probe the high-density behavior of the nuclear symmetry energy. Currently, to pin down the symmetry energy, the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University, the Gesellschaft fuer Schwerionenforschung (GSI) at Darmstadt, the Rikagaku Kenkyusho (RIKEN, The Institute of Physical and Chemical Research) of Japan, and the Cooler Storage Ring (CSR) in Lanzhou, are planning to do related experiments. Effects of the symmetry energy on the pre-equilibrium neutron/proton ratio in heavy ion collisions have been analyzed with many authors. For example, calculations by Zhang et al.[8] within the Improved Quantum Molecular Dynamics(ImQMD) model using two different density-dependent symmetry-energy functions, the results of neutron to proton ratios are sensitive to the density dependence of the symmetry energy. Within the transport model Lanzhou Quantum Molecular Dynamics(LQMD),

Feng [9] investigated the single and double neutron to proton ratio of free nucleons with different collision centralities and effective mass splitting. Recently, Ma et al.[10] studied the high-density behavior of the symmetry energy by using single and double ratios of neutrons to protons within Isospin Quantum Molecular Dynamics(IQMD) model, they confirmed that it is possible to study the high-density behavior of symmetry energy by using the neutron-to-proton ratio from free nucleons. In the present work we give our results of the effects of symmetry energy on free neutron to proton ratio as a function of rapidity in the $^{40}\text{Ca}+^{124}\text{Sn}$ at 140 MeV/nucleon. We find that nucleon emissions at low-angle and large rapidities regions are suitable to be used to probe the effect of symmetry energy. The free n/p ratios at large or small rapidities may reflect low or high density behavior of symmetry energy.

II. THE IBUU04 TRANSPORT MODEL

Our present study is based on the transport model IBUU04. In this semi-classical model besides nucleons, Δ and N^* resonances as well as pions and their isospin-dependent dynamics are included, the experimental free-space nucleon-nucleon (NN) scattering cross sections and the in-medium NN cross sections can be used optionally. By using the relativistic mean field theory, the initial neutron and proton density distributions of the projectile and target are obtained. The isospin dependent phase-space distribution functions of the particles involved are solved by using the test-particle method numerically. The isospin-dependence of Pauli blockings for fermions is also considered. More details can be found in Refs. [12–17]. In the present work, we use the isospin-dependent in-medium NN elastic cross sections from the scaling model according to nucleon effective masses [13]. In the IBUU04 transport model, the most important input is the momentum- and isospin-dependent single nu-

cleon potential, we use a single nucleon potential derived within the Hartree-Fock approach using a modified Gogny effective interaction [12], the momentum-dependent single nucleon potential (MDI) adopted here is:

$$\begin{aligned}
 U(\rho, \delta, \mathbf{p}, \tau) = & A_u(x) \frac{\rho_{\tau'}}{\rho_0} + A_l(x) \frac{\rho_{\tau}}{\rho_0} \\
 & + B \left(\frac{\rho}{\rho_0} \right)^{\sigma} (1 - x\delta^2) - 8x\tau \frac{B}{\sigma+1} \frac{\rho^{\sigma-1}}{\rho_0^{\sigma}} \delta \rho_{\tau'} \\
 & + \frac{2C_{\tau,\tau}}{\rho_0} \int d^3\mathbf{p}' \frac{f_{\tau}(\mathbf{r}, \mathbf{p}')}{1 + (\mathbf{p} - \mathbf{p}')^2/\Lambda^2} \\
 & + \frac{2C_{\tau,\tau'}}{\rho_0} \int d^3\mathbf{p}' \frac{f_{\tau'}(\mathbf{r}, \mathbf{p}')}{1 + (\mathbf{p} - \mathbf{p}')^2/\Lambda^2}. \quad (1)
 \end{aligned}$$

In the above equation, $\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$ is the isospin asymmetry parameter, $\rho = \rho_n + \rho_p$ is the baryon density and ρ_n, ρ_p are the neutron and proton densities, respectively. $\tau = 1/2(-1/2)$ for neutron (proton) and $\tau \neq \tau'$, $\sigma = 4/3$, $f_{\tau}(\mathbf{r}, \mathbf{p})$ is the phase-space distribution function at coordinate \mathbf{r} and momentum \mathbf{p} . The parameters $A_u(x), A_l(x), B, C_{\tau,\tau}, C_{\tau,\tau'}$ and Λ were set by reproducing the momentum-dependent potential $U(\rho, \delta, \mathbf{p}, \tau)$ predicted by the Gogny Hartree-Fock and/or the Brueckner-Hartree-Fock calculations. The momentum-dependence of the symmetry potential stems from the different interaction strength parameters $C_{\tau,\tau'}$ and $C_{\tau,\tau}$ for a nucleon of isospin τ interacting, respectively, with unlike and like nucleons in the background fields, more specifically, $C_{unlike} = -103.4$ MeV while $C_{like} = -11.7$ MeV. The parameters $A_u(x)$ and $A_l(x)$ depend on the x parameter according to $A_u(x) = -95.98 - x \frac{2B}{\sigma+1}$ and $A_l(x) = -120.57 + x \frac{2B}{\sigma+1}$. The saturation properties of symmetric nuclear matter and the symmetry energy of about 32 MeV at normal nuclear matter density $\rho_0 = 0.16 \text{ fm}^{-3}$. The incompressibility of symmetric nuclear matter at normal density is set to be 211 MeV. According to essentially all microscopic model calculations, the EOS for isospin asymmetric nuclear matter can be expressed as

$$E(\rho, \delta) = E(\rho, 0) + E_{\text{sym}}(\rho)\delta^2 + \mathcal{O}(\delta^4), \quad (2)$$

where $E(\rho, 0)$ and $E_{\text{sym}}(\rho)$ are the energy per nucleon of symmetric nuclear matter and nuclear symmetry energy, respectively. For a given value x , with the single particle potential $U(\rho, \delta, \mathbf{p}, \tau)$, one can readily calculate the symmetry energy $E_{\text{sym}}(\rho)$ as a function of density.

III. RESULTS AND DISCUSSIONS

Fig. 1 shows the density dependence of nuclear symmetry energy with parameter $x = 1, 0$, respectively. As discussed in the previous part, the single particle potential used has an x parameter, different specific x parameter denotes different density dependent symmetry energy. For the central reaction $^{40}\text{Ca} + ^{124}\text{Sn}$ at 140

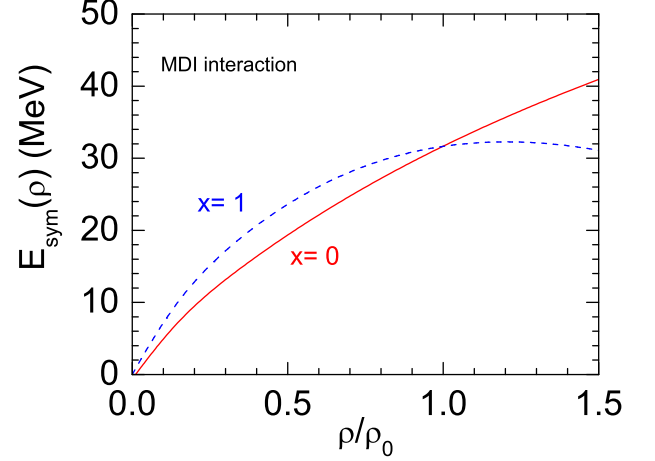


FIG. 1: (Color online) Density dependence of nuclear symmetry energy with parameters $x = 1, 0$, respectively.

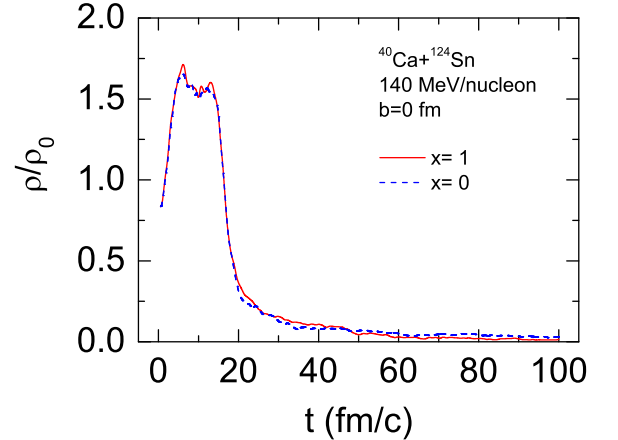


FIG. 2: (Color online) Maximal baryon density reached in the central reaction $^{40}\text{Ca} + ^{124}\text{Sn}$ at 140 MeV/nucleon.

MeV/nucleon, the maximal density reached is about 1.5 times saturation density as shown in Fig. 2. We therefore only show the low density's symmetry energy as a function of density. From Fig. 1, we can also see that the low density behaviors of nuclear symmetry energy separate from each other with different x parameters. At the saturation point there is a cross and then they separate from each other again. At lower densities, the value of symmetry energy of $x = 0$ is lower than that of $x = 1$. But at high densities, the value of symmetry energy of $x = 0$ is higher than that of $x = 1$. From Fig. 2, we can see that at the reaction time $t = 50 \text{ fm/c}$, the reaction

almost ends.

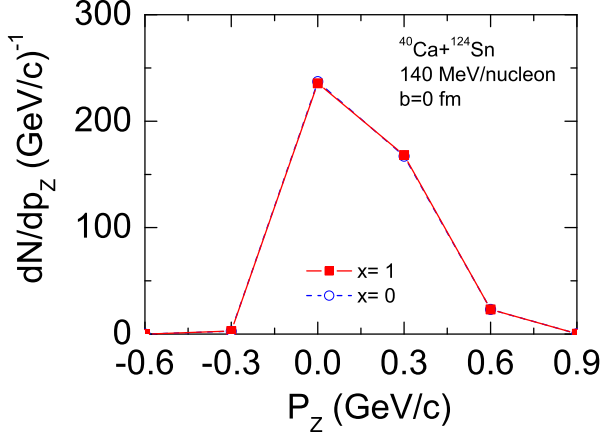


FIG. 3: (Color online) Longitudinal momentum (p_z) distribution of emitted free nucleons in laboratory system in the central reaction $^{40}\text{Ca}+^{124}\text{Sn}$ at 140 MeV/nucleon.

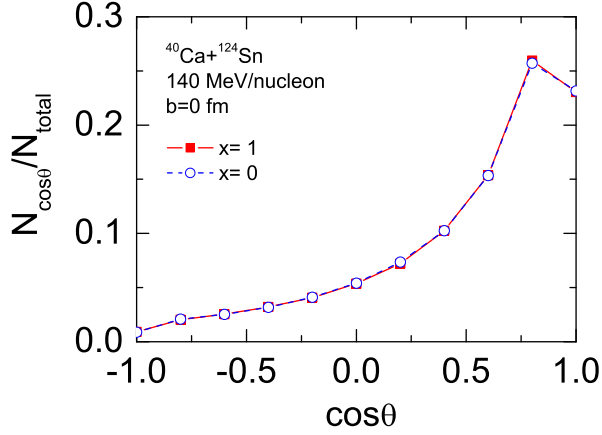


FIG. 4: (Color online) Angle distribution of relative emitted number ($N \cos \theta / N_{\text{total}}$) of the free nucleons in laboratory system in the central reaction $^{40}\text{Ca}+^{124}\text{Sn}$ at 140 MeV/nucleon.

Fig. 3 shows the longitudinal momentum (p_z) distribution of emitted free nucleons in laboratory system in the central reaction $^{40}\text{Ca}+^{124}\text{Sn}$ at 140 MeV/nucleon. In our work, free nucleons are identified as those having local baryon densities less than $\rho = \frac{1}{8}\rho_0$. We can first see that more nucleons are emitted at positive momentum part than at the negative part. Also one can see that longitudinal momentum (p_z) distribution of emitted free nucleons is insensitive to the symmetry energy since the

effects of symmetry energy are always very small. The maximal longitudinal momentum at positive momentum part reached is about 0.9 GeV/c, but the maximal longitudinal momentum at negative momentum part reached is only about 0.3 GeV/c. From this plot we can clearly see that most emissions are at very small longitudinal momentum (p_z), denoting that more nucleons may emitted perpendicularly to the reaction plane. Experimentally, one always needs to know the angle distribution of the emitted number of probed nucleons in the reaction. This is because one usually can not probe the emitted particles in 4π directions. For this purpose, we plot Fig. 4, the angle distribution of relative emitted number ($N \cos \theta / N_{\text{total}}$) of the free nucleons in laboratory system in the central reaction $^{40}\text{Ca}+^{124}\text{Sn}$ at 140 MeV/nucleon. From this plot, we can clearly see that whether for $x = 1$ or $x = 0$ nucleons are inclined to low-angle emission. It is thus suitable to probe the emitted nucleons in the low-angle regions.

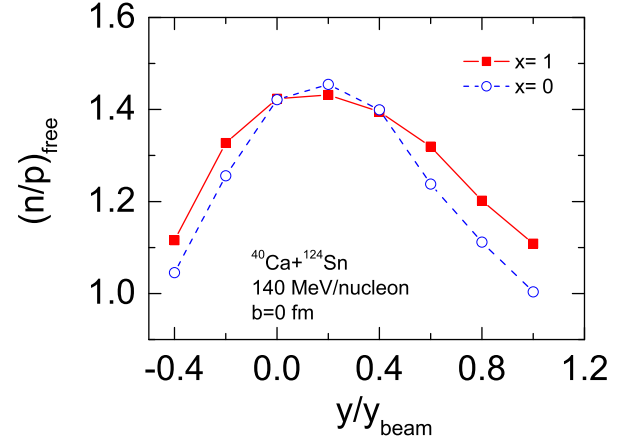


FIG. 5: (Color online) Neutron to proton ratio (n/p) of the emitted free nucleons as a function of reduced rapidity with $x = 1$ and 0 in laboratory system in the central reaction $^{40}\text{Ca}+^{124}\text{Sn}$ at 140 MeV/nucleon.

To see the effects of symmetry energy on emitted free neutron to proton ratio, we provide Fig. 5, the neutron to proton ratio (n/p) of the emitted free nucleons as a function of reduced rapidity with $x = 1$ and 0 in laboratory system in the central reaction $^{40}\text{Ca}+^{124}\text{Sn}$ at 140 MeV/nucleon. From this plot we can see that at large rapidities, effects of symmetry energy are clearly shown on the neutron to proton ratio. The soft symmetry energy ($x = 1$) corresponds large n/p ratio than the stiff case ($x = 0$), the n/p ratio thus reflects the low-density behavior of nuclear symmetry energy. Around low rapidity $y/y_{\text{beam}} = 0.2$, the stiff symmetry energy corresponds large n/p ratio, reflecting the high-density behavior of nuclear symmetry energy. This indicates that nucleons

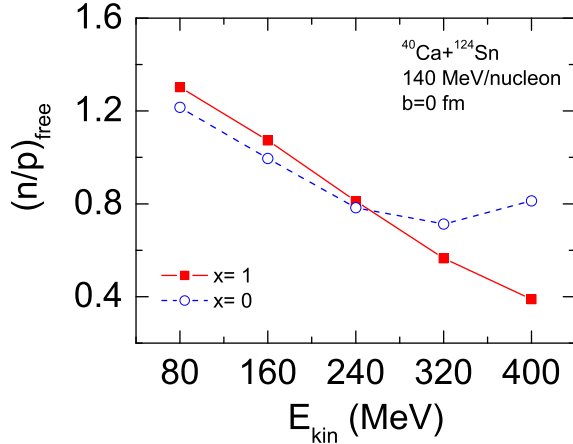


FIG. 6: (Color online) Neutron to proton ratio (n/p) of the emitted free nucleons as a function of kinetic energy with $x=1$ and 0 in laboratory system in the central reaction $^{40}\text{Ca}+^{124}\text{Sn}$ at 140 MeV/nucleon .

around low rapidity $y/y_{\text{beam}} = 0.2$ are from high-density region of compressed nuclear matter, and this part of emitted nucleons has a large number (also as shown in Fig. 3). Thus the free n/p ratios at large or small rapidities may reflect low or high density behavior of symmetry energy. And because the emitted nucleons are mainly at low-angle regions (shown in Fig. 4), we deduce that the better way to probe the effects of symmetry energy on free neutron to proton ratio n/p is probing the emitted nucleons at large rapidities and low-angle regions in laboratory system in the central reaction $^{40}\text{Ca}+^{124}\text{Sn}$ at 140 MeV/nucleon .

Fig. 6 shows the neutron to proton ratio (n/p) of the emitted free nucleons as a function of *kinetic energy* with $x = 1$ and 0 in laboratory system in the central reaction $^{40}\text{Ca}+^{124}\text{Sn}$ at 140 MeV/nucleon . We can see that the stiff symmetry energy ($x = 0$) corresponds large n/p at higher kinetic energies. At lower kinetic energies the soft symmetry energy ($x = 1$) corresponds larger n/p . From Fig. 6 and Fig. 5, we can again deduce that nucleons at small rapidities mainly come from the compressed nuclear matter, which have large kinetic energies, their n/p ratios reflect high density behavior of nuclear symmetry energy. Nucleons at large rapidities mainly come from the low-density nuclear matter, which have no very large kinetic energies, their n/p ratios reflect low density behavior of nuclear symmetry energy. From above

discussions, in the central reaction $^{40}\text{Ca}+^{124}\text{Sn}$ at 140 MeV/nucleon , to probe the high density behavior of nuclear symmetry energy, we can probe nucleons at very high kinetic energies and at mid-rapidities. To probe the low density behavior of nuclear symmetry energy, we can probe nucleons at not very high kinetic energies and at large rapidities. Therefore, to probe the symmetry energy, it is better to give the kinetic distribution and the rapidity distribution of emitted nucleons at the same time.

IV. SUMMARY

Based on the semiclassical Boltzmann-Uehling-Uhlenbeck (BUU) transport model, we studied the effects of symmetry energy on the free neutron to proton ratio in the central reaction $^{40}\text{Ca}+^{124}\text{Sn}$ at 140 MeV/nucleon in the laboratory system. It is found that at large rapidities free nucleon's neutron to proton ratio is quite sensitive to the symmetry energy. And we also find that free nucleons are mainly emitted at low-angle regions and at *zero* longitudinal momentum (p_z) in the laboratory system. The maximal longitudinal momentum at positive momentum part reached is about 0.9 GeV/c , but the maximal longitudinal momentum at negative momentum part reached is only about 0.3 GeV/c . And more nucleons are emitted at positive momentum part (mainly in the range of $0 < p_z < 0.3 \text{ GeV/c}$) than at the negative part. The free n/p ratios at small or large rapidities may reflect high or low density behavior of nuclear symmetry energy. These information is useful for related experiments relevant to symmetry energy studies.

Acknowledgments

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